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Combustion Recovery: A Measurement of Fire Retardant Extinguishment Capability

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RESEARCH SUMMARY

This study describes a laboratory method (and results) for quantifying the fire-extinguishing capabilities of different water/chemical combinations commonly used to suppress fires. Pine needle fuel beds were ignited and allowed to reach maximum steady-state energy release. They were then sprayed with fire retardants to decrease the energy release rates to different levels above zero. After measured applications were made, the steady-state energy release rate and its duration after the combustion had recovered were recorded by monitoring the weight loss of the treated fuels as they burned. Energy release rates and duration were compared for fires sprayed with water, water mixed with different amounts of fire retardant chemicals, and water mixed with different amounts of guar gum thickener.

Combustion recovery data from these demonstration fires indicate that plain water is the principal agent to initially decrease both flaming and smoldering combustion. Adding retardant chemicals did not improve flame "knockdown" capabilities of water, but the chemical additives minimized subsequent rate and duration of energy release. The test method was sensitive enough to show that solutions of monoammonium phosphate are more effective in slowing combustion recovery than plain water, and that a slightly thickened solution slowed recovery more than either an unthickened solution or one thickened to 900 cP.

Combustion Recovery: A Measurement of Fire Retardant Extinguishment Capability

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INTRODUCTION

Water or water with chemicals added (retardants) is commonly used to combat wildland fires by two general application methods—applying liquid directly to flaming combustion (direct attack) or to unburned fuels that are in the path of the fire (indirect attack). The direct method is usually intended to control fire by totally extinguishing all combustion. Assuming correct placement of retardant, total extinguishment (stopping both smoldering and flaming combustion) success is usually dependent on the fire intensity, fuel loading and arrangement, and total volume of liquid and its application rate. Direct attack is meant to absorb the propagating heat flux and decrease the oxygen supply sufficiently to stop all combustion. Indirect attack is also intended to absorb heat energy, plus chemically alter the pyrolysis of rapidly heating fuels enough to change the composition and flammability of evolved products. Combinations of these two general methods are used, depending on the fire/fuel situation. Even though the indirect method may be more efficient in many instances (no evaporation above the flames), the direct method is very frequently used on wildland fires with both aerial and ground application.

Numerous methods have been used under controlled conditions to determine the effectiveness of water and retardants for extinguishing combustion. One principal method has been to spray water or retardants onto flaming fuels of different types and arrangements. Different retardants may have similar capabilities for reducing flaming combustion but be very different in their ability to maintain that reduced state. The water in the retardant appears to be the principal agent to reduce the flaming by absorbing heat energy, diluting flammable gases, and smothering to reduce oxygen availability. The retardant chemicals act to change the flammability and quantity of evolving gases (Philpot 1971) and to change the droplet sizes and flow characteristics of the water (Andersen and Wong 1978). Measuring specific effects on fire behavior is difficult and has been done with very general parameters such as total energy release (USDA 1955), flame height (Johanson 1967), flame temperatures (Hardy and others 1962), emitted radiant energy (Phillips and Miller 1959; Dibble and others 1961; USDA 1955), times until flaming or glowing stopped (Truax 1939; Grove and others 1962), and total amount of liquid required to reach a predetermined combustion state and application rates needed to produce that state (Truax 1939; Tyner 1941; George and Blakely 1972).

This study compares energy release rates (E_R) of burning fuel beds sprayed with various water or chemical treatments. When liquid is insufficient to stop all combustion, flaming recurs (combustion recovery) because fuels beneath the level of treatment penetration continue to smolder. The heat of smoldering combustion dries and reignites fuels and sustains combustion—unless additional liquid is applied. In this study, increased amounts of liquid are applied to successive identical fires and the results are monitored until so large a volume is applied that all combustion ceases soon after application is stopped.

Although two of the same parameters (energy release rate and total application) used in other studies are being measured, in this study they are used to examine the consequences when the combustion is not totally extinguished and what differences on long term effects (time to recovery and E_R) there are between application rates, total application, retardant salt concentrations, and viscosities. This study method was designed to determine the importance of water in decreasing flaming combustion, with and without fire-retarding chemicals, and also to what extent the chemicals remaining after evaporation prevent or retard combustion recovery and subsequent fire propagation and spread.

EXPERIMENTAL METHOD FOR QUANTIFYING COMBUSTION RECOVERY

Individual fires were sprayed with small amounts of water or water that contained chemicals, and magnitude and duration of E_R were recorded. If too much chemical or water was used, the fire would be extinguished and the amount of excess liquid not known. In pine needle fuel beds it is very difficult (if not impossible) to visually determine when the fire is totally out and therefore when to stop applying water. In past extinguishment tests, the fire was sprayed until the flames were visually out, then again until all smoldering (smoking) was stopped (Truax 1939; Grove 1962). The tests quantified how much water/chemical is required to provide different stages of extinguishment (flames out and smoldering out). They did not take into account situations when insufficient water/chemical was applied.

Because extinguishment is difficult to determine visually, the method used in this study conducts several trials by adding small amounts of water or retardant salt or more thickening agent to successive fires until combustion does not recover (determined by monitoring weight loss). This method reveals a definite point when combustion stops.

Plain water or water that contains fire-retarding chemicals, with and without thickening agents, was applied to burning pine needle fuel beds from a trolley-mounted spray nozzle (fig. 1) above the fuel beds. The nozzle size, pressure, and trolley speed controlled the amount of retardant applied to each burning fuel bed. Effect on combustion was determined by continuously monitoring the weight loss of the burning fuel. Weight loss can be related directly to E_R by associating the fuel weight loss rate with the measured heat content for the specific fuel (Rothermel and Anderson 1966; George and Blakely 1970).

Fuel beds were 4 ft long, 3 ft wide, and 3 inches deep, using 4 lb of ponderosa pine needles. The fuel loading was 0.33 lb/ft^2 and the bulk density was 1.33 lb/ft^3. Needles were dried to equilibrium at room temperature and fuel moisture content was from 6 to 7.5 percent by weight. Fuels were burned in a wind tunnel under controlled conditions of 5 mi/h (±0.5), 90 °F (±2°), and 20 percent (±2 percent) R.H. (These environmental conditions can be related to wildfire situations by the following: When needles are classed as fuel type U, the National Fire-Danger Rating System (NFDRS) grades fires in untreated fuels as spread component 5, energy release component 38, and burning index 34.) Calculated using 8,745 Btu/lb, the entire fuel bed contained a potential of approximately 34,982 Btu. The average maximum untreated burning rate for five untreated fires averaged 296 Btu/s, with flame lengths reaching 3 to 4 ft. Ninety-five percent of the total energy potential (33,233 Btu) was expended within 4 minutes.

The fuel bed was ignited in a manner that insured rapid ignition of the entire surface. A 15-ft cord that had been soaked in xylene was laid along each side, down the middle of the bed, and across the upwind end. The upwind center of the cord was ignited by an electric hot wire and the fire spread along the cord to ignite the fuel bed edges and center within 10 seconds. Within 20 seconds of ignition, the entire surface of the bed was flaming. The fire was allowed to burn downward into the bed until the maximum E_R was detected and had begun to level off. The maximum E_R occurred approximately 45 seconds after ignition. At that time the extinguishant was applied to the flaming fuel bed. Approximately 27 percent of the total fuel weight had been consumed before the sprayer was turned on.

Energy Release Measurement

To measure total E_R, the fuel bed was placed on a top-loading digital balance that was connected through a digital/analog converter to a microcomputer (fig. 1). The computer was programmed to record weight changes during sprayer calibration and while the fuel was burning and being extinguished. The computer displayed four parameter traces versus time: total weight, radiation, sprayer tank pressure, and manually activated event

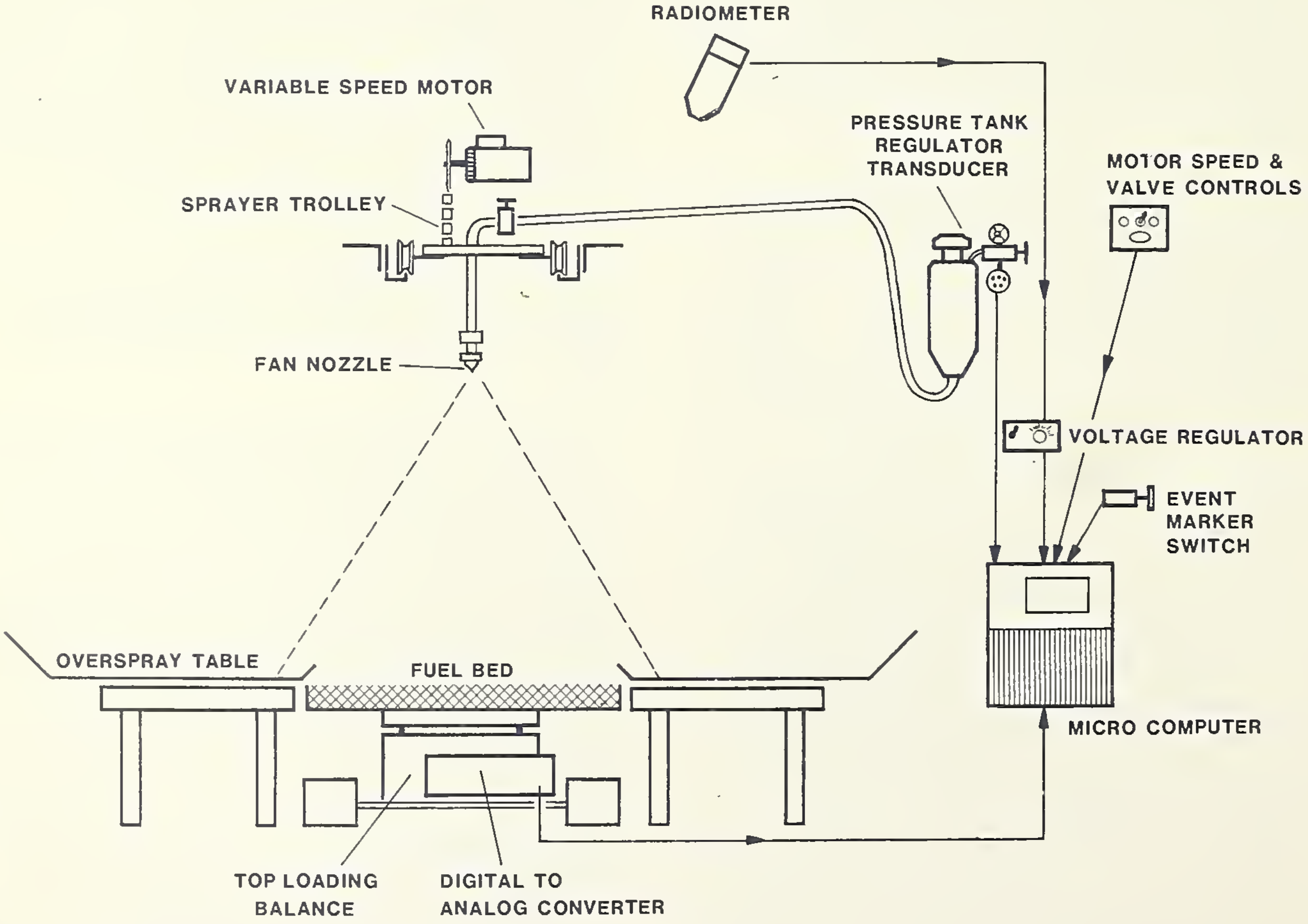

Figure 1.—Overhead sprayer and fuel bed weighing system.

marks. All data were recorded on tape for later transfer to a computer disk.

To quickly determine E_R (difficult with the weight loss trace), a Gier-Dunkle directional radiometer was mounted above the fuel bed and to one side (fig. 1). The irradiance data were transmitted directly to the microcomputer and recorded as millivolts. When the irradiance trace reached a maximum rate, the water/chemical application was started. The radiometer was attached to the top of the tunnel 8.4 ft above the top surface of the fuel bed. It was 3.2 ft to the side of the bed and was tilted 67° downward to have maximum viewing of the width of the fuel bed. The placement of the radiometer in this position allowed it to receive irradiance from the entire fuel bed surface and up to 4-ft flame heights.

Liquid Application

Water or water that contained monoammonium phosphate (MAP) with and without guar gum thickener was directed to the flaming fuel with an overhead nozzle that delivered a flat, fan-shaped pattern. A 2-gal pressurized tank was mounted outside the wind tunnel with a flexible tube that ran up the tunnel wall and across the top to a movable trolley. The tubing was connected to a pipe that extended down from the trolley and placed the nozzle tip 6.23 ft above the fuel bed surface. An electric solenoid activated a valve just ahead of the nozzle for instantaneous on and off flow. The valve design was straight-through flow to prevent shearing the liquid, which might change the viscosity and thus droplet sizes.

The trolley was moved over the bed by a variable-speed motor and sprocket-chain drive that were controlled from outside the wind tunnel. The sprayer was calibrated by placing a large aluminum pan, the same size as the fuel bed, on the balance and spraying liquid onto it. The balance was connected to the microcomputer that calculates the total application and rate of liquid falling onto the pan surface. Small narrow trays laid in the large tray were used to determine the uniformity of chemical coverage across the bed perpendicular to the direction of nozzle movement. The coverage was adjusted to a consistent pattern by varying pressure in the spray tank and nozzle height above the fuel. Droplet size and flow rate were varied by changing pressure and nozzle size. Total application and rate were controlled by the speed at which the trolley carried the nozzle along the full length of the fuel bed.

An example of energy release, from fuel bed ignition until all combustion stops, is shown in figure 2. Control beds with no liquid application (weight loss trace J) were ignited and allowed to burn freely until all combustion had stopped. The entire fuel bed surface was burning within 6 seconds, then E_R increased rapidly as the fire progressed downward into the fuel. The E_R increased for about 90 seconds then started to drop off slowly. By the time the highest combustion rate was reached, only about 27 percent of the fuel had been consumed. Within 4 minutes, 95 percent of the total bed weight was consumed and part of the remaining 5 percent was consumed (mainly by smoldering combustion) very slowly over the next 15 minutes. The highest combustion rate was about 300 Btu/s. After 95 percent fuel consumption, the rate was about 15 Btu/s; after 10 minutes about 7 Btu/s.

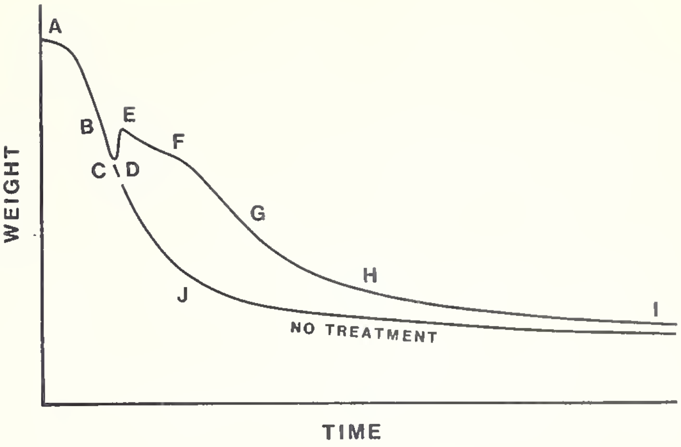

Figure 2.—Typical stages of fuel bed weight loss during retardant experiments.

When water/chemical is applied, the immediate decrease in flaming combustion depends on the total volume of water applied. Early in the study during preliminary burns, it was recognized that water was the principal factor contributing to flame extinction; therefore, comparison treatments were changed from equal weights of liquid (with and without retardant chemicals) to equal weights of water with different weights of chemical added as the variable. Designated segments (noted with capital letters) of the weight loss curve are for tests with liquid applied and are shown in figure 2. The weight loss trace shows a rapid loss for a few seconds, then E_R is at a steady-state for up to 4 minutes (depending on application), then increases again but has another steady-state period before gradually decreasing until burnout. (A steady-state period is one during which the rate of energy release remains constant.) The following is an explanation of each general segment of the weight loss curve example in figure 2.

Segment A.	Slight weight loss caused by burning xylene and fuel.
Segment B.	Surface of fuel bed becomes totally involved and maximum energy release rate occurs.
Segment C.	During maximum E_R, chemical is applied to burning fuel bed starting at downwind end. The sprayer moves upwind covering entire fuel bed from front to rear and side to side within 2 to 10 seconds, depending on the trolley speed and the amount of liquid application.
Segment D.	As more and more liquid contacts the flaming bed, the weight loss rate begins to decrease and the added liquid causes the total fuel bed weight to increase. Application rate becomes same as weight loss rate for a short period.
Segment E.	The sprayer is shut off and total weight begins to show a decline again, but offset in time and at a different rate from the untreated burning rate. Flaming combustion is at a minimum. In some cases the force of the retardant hitting the bed

causes the recorder trace to drop when the sprayer is shut off. (This should not be confused with a sudden E_R decrease.)

Segment F. First steady-state period—E_R is at a minimum in this area as the water/chemical affects the combustion rate. As the water evaporates, flaming increases except when there is sufficient chemical on the fuel to strongly affect pyrolysis. If the total application of solution is enough to penetrate to the smoldering fuels the flaming will be suppressed even longer or stopped.

Segment G. Second steady-state period—most, if not all, of the water is evaporated and E_R begins to increase. Water-only treatments are totally evaporated in this area and the E_R rate approaches that of untreated fuel.

Segment H. Approximately 75 percent of fuel has been consumed—most of the water has evaporated, chemical effects on pyrolysis are minimal. H to I is mostly smoldering combustion with some short reflaming caused by glowing combustion underneath the surface. E_R for lower water treatments is the same as untreated. Increased water treatments and middle to heavy chemical treatments cause H to I to stay above the untreated total weight loss, but the curve shapes are similar, indicating weight loss is caused by smoldering combustion below the fuel bed surface.

RESULTS

Data from eight test fires were selected to demonstrate how this application method and E_R interpretation can be used to quantify the fire-extinguishing effects of water and retardant. Table 1 shows the application data and resultant E_R modifications. The letter A designates water; B is 10 percent monoammonium phosphate (MAP); and C is 15 percent MAP. X, Y, and Z designate water and retardant mixtures thickened with polysaccharide to 1 cP, 55 cP, or 900 cP viscosities (measured with No. 3 and No. 4 spindles using a Brookfield viscometer at 60 r/min).

Steady-state E_R and duration are determined from straight-line weight loss on the curves. Untreated fires have only one steady-state period, during maximum E_R. All the treated test fires reported here have at least three steady-state periods: one during maximum weight loss before retardant application, one just after the application has stopped, and at least one before the weight loss rate begins to decrease steadily and continue to burn out.

To isolate the effects of retardant viscosity on E_R, application of total weight of water and retardant chemical were held constant. Differences between E_R magnitudes and durations before and after treatments were compared for fires BX216, BY216, and BZ216. Two hundred and forty grams of 10 percent MAP solution were applied with 1 cP, 55 cP, and 900 cP viscosities. BX216 (1 cP) reduced E_R (1st steady-state) by 97.0 percent, BY216 (55 cP) by 97.5 percent, and BZ216 (900 cP) by 93.5 percent. The most obvious difference is between the high viscosity retardant, BZ216, and the low viscosity solutions.

Examining the weight loss curves (fig. 3), we see that BY216 application lowered E_R to a steady-state 7.7 Btu/s (about the same as untreated after fire had burned for 10 minutes) for about 2.80 minutes. The E_R then increased to 15.6 Btu/s for 2.08 minutes before starting a slow decrease in rate until burnout. In comparison, BX216 burned at 9.3 Btu/s for 2.35 minutes then increased sharply to 19.7 Btu/s for 2.28 minutes before burnout. BZ216 burned at 18.8 Btu/s for 2.15 minutes then increased to 34.8 Btu/s for 4.02 minutes.

The effects of retardant chemical on E_R reduction, with total volume of water and viscosity of liquid held constant, can be found by comparing fires AY216, BY216, and CY216. Treatment BY216 (24 g MAP) reduces E_R by 97.5 percent, AY216 (no MAP) by 84.5 percent, and CY216 (38 g MAP) by 98.1 percent. Penetration should be about the same for all because liquid volume and viscosity are identical. In this case, the more retardant chemical added, the more the E_R reduction. An additional 14 g of MAP did not proportionally increase the effectiveness of the treatment but did extend the time of effectiveness.

Examining the weight loss curves (fig. 4) we see that CY216 application reduces E_R to a steady-state 5.4 Btu/s for 5.22 minutes, then increases to 15.6 Btu/s for

Table 1.—Treatment data and resultant energy release modifications for each burn

	Treatment			Energy release rate						
				Before	First steady-state			Second steady-state		
Designation	Water	MAP	Viscosity	treatment	Btu/s	Reduction	Duration	Btu/s	Reduction	Duration
	--- Grams	*---*	*cP*	*Btu/s*		*Percent*	*Min*		*Percent*	*Min*
BX216	216	24	1	308	9.3	97.0	2.35	19.7	93.6	2.28
BY216	216	24	55	308	7.7	97.5	2.80	15.6	94.9	2.08
BZ216	216	24	900	289	18.8	93.5	2.15	34.8	88.0	4.02
BY180	180	20	55	280	7.7	97.2	3.13	17.2	93.9	1.73
BY144	144	16	55	308	12.4	96.0	3.05	39.3	87.2	2.03
AY216	216	0	55	330	51.0	84.5	1.28	115.0	65.2	1.03
CY216	216	38	55	280	5.4	98.1	5.21	15.6	94.4	4.88

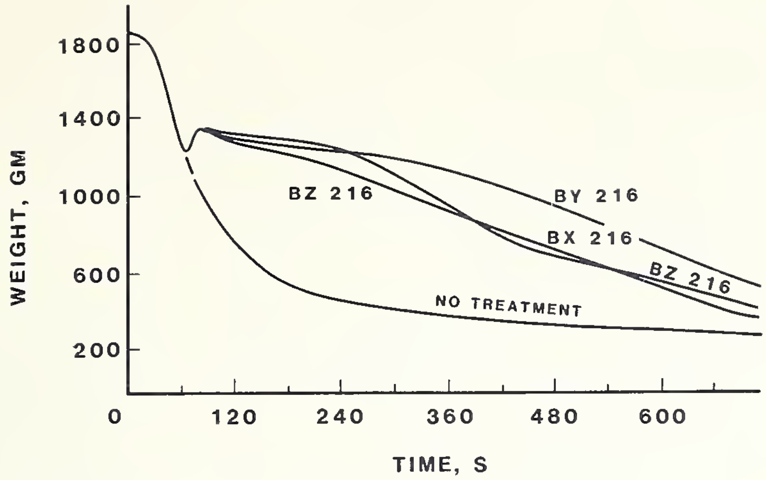

Figure 3.—Fuel weight loss traces when viscosity was varied.

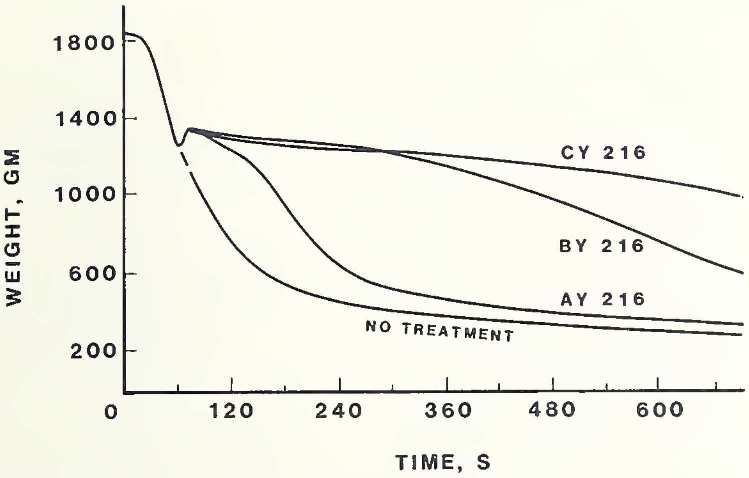

Figure 4.—Fuel weight loss traces when retardant chemical was varied.

4.88 minutes. AY216 reduces E_R to 51 Btu/s for only 1.28 minutes, then increases to 115 Btu/s for 1.03 minutes. (BY216 is listed previously.) The three curves clearly show that compared to water alone addition of MAP significantly reduces E_R and lengthens the time of various levels of energy release.

The effects of retardant volume on reduction of E_R, when viscosity (55 cP) and liquid concentration (10 percent) are constant, can be seen by comparing fires BY144, BY180, and BY216. Treatment BY216 (240 g) reduces E_R by 97.5 percent, BY180 (200 g) by 97.2 percent, and BY144 (160 g) by 96.0 percent. In this comparison, each higher total volume results in a slightly lower E_R.

Examining the weight loss curves (fig. 5) we see that BY144 decreases E_R to 12.4 Btu/s for 3.05 minutes, then E_R increases to 39.3 Btu/s for 2.03 minutes. BY180 decreases E_R to 7.7 Btu/s for 3.13 minutes, then E_R increases to 17.2 Btu/s for 1.73 minutes (BY216 is listed previously). The most obvious differences occur after about 5 minutes; the higher the total volume of liquid applied, the lower E_R remains through burnout.

SUMMARY AND CONCLUSIONS

For the purposes of this study, combustion recovery is defined as flaming and smoldering that can recur shortly after combustion appears to have been suppressed by fire retardant. Combustion recovery was used in this study to compare the fire-extinguishing abilities of different fire retardant characteristics and was measured in terms of energy release rate (E_R) of burning pine needles. E_R was calculated from steady-state segments of fuel weight loss curves recorded as treated and untreated fuels burned under controlled conditions. Steady-state E_R and duration were used to quantify fire-extinguishing abilities of three different fire retardant characteristics, total volume of liquid applied, viscosity, and weight of retardant chemical. Seven treatments of experimental fires were selected to demonstrate how this method can be used to quantify effectiveness differences.

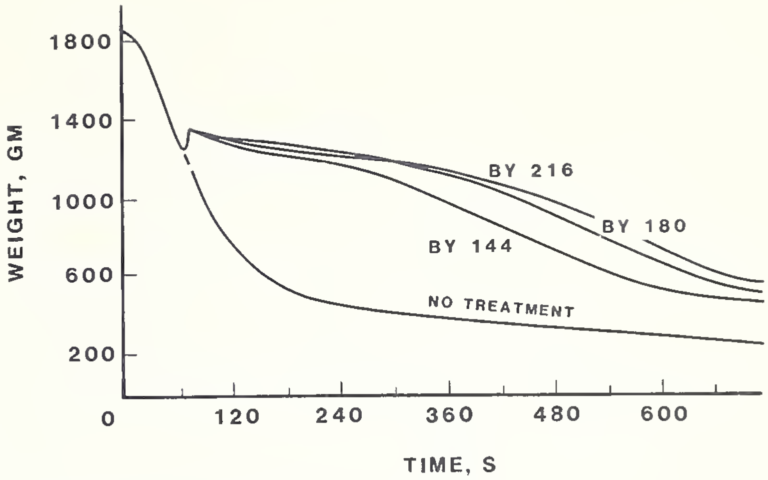

Figure 5.—Fuel weight loss traces when water amount was varied.

When total weight of water and amount of retardant chemical were held constant, the weight loss curves showed differences in E_R caused by the retardant viscosities, 1 cP, 55 cP, and 900 cP. From previous studies we know that at higher viscosities retardants form larger droplets that are more likely to penetrate the flame plume. Results of this study indicate that the slightly viscous water and retardants reduce E_R of combustion recovery slightly more than unthickened or high-viscosity liquids. Although the high-viscosity liquids penetrate the flame plume better than low-viscosity ones, in this mat-type fuel bed they may not penetrate as deeply into the smoldering fuel levels and, thus, not coat as much fuel. This theory can be studied more thoroughly in future experiments.

The effects of retardant chemical on reducing E_R were studied by holding volume of water and liquid viscosity constant. The steady-state E_R curve segments can be used to show definite differences between retardant chemical applications; the more retardant applied, the more E_R is reduced. Although in these examples the highest treatment was twice as heavy as the next lower, the reduction in E_R was only slightly more, but the duration was twice as long. The addition of an equal amount of water with no chemical was almost 10 times less effective than either water chemical treatment.

The effects of total liquid weight were studied by holding viscosity and liquid concentration constant and varying the weight of liquid applied. In the examples shown here, the larger the treatment the larger the decrease in E_R and the longer its duration.

Selected data from this method of measuring the combustion recovery can be used to quantify the E_R reduction caused by different fire retardant characteristics. The different fires and treatments were used only to evaluate the method and were not replicated and evaluated statistically, but the limited data show that real differences can be quantified for the different variables. Replications of treatments and fires with different fuel types and environmental conditions are needed to fully study the effects of retardants on combustion recovery and extinguishment.

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Proposes a method for quantifying the fire-extinguishing capabilities of plain water and water with thickeners and fire-retarding chemicals added. Flaming pine needle fuel beds were sprayed with different water/chemical combinations while energy release rates were continuously monitored before and after treatment. Discusses the action of common retardant formulations and specific ingredients.

KEYWORDS: fire retardant, extinguish, energy release, combustion recovery

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